

Biological Phosphorus Removal
A Technology Evaluation

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Prepared for

Environmental Protection Agency, Cincinnati, OH

Nov 85



U.S. Department of Commerce
National Technical Information Service

NTIS

EPA/600/D-85/289
November 1985

BIOLOGICAL PHOSPHORUS REMOVAL:
A TECHNOLOGY EVALUATION

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SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA (Please read instructions on the reverse before completing)		
1. REPORT NO. EPA/600/D-85/289	2.	3. RECIPIENT'S ACCESSION NO. PBB 6 1267527AS
4. TITLE AND SUBTITLE Biological Phosphorus Removal: A Technology Evaluation		5. REPORT DATE November 1985
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Mark J. Tetreault, Arthur H. Benedict, Christopher Kaempfer, and Edwin F. Barth		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Brown and Caldwell 3480 Buskirk Avenue Pleasant Hill, CA 94523		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. 68-03-1818
12. SPONSORING AGENCY NAME AND ADDRESS Water Engineering Research Laboratory --Cinti. OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, OH 45268		13. TYPE OF REPORT AND PERIOD COVERED
		14. SPONSORING AGENCY CODE EPA/600/14
15. SUPPLEMENTARY NOTES Project Officer: James A. Heidnan (513) 569-7632 Comm.; 684-7632 FTS		
16. ABSTRACT A study of alternative biological phosphorus (bio-P) removal processes was undertaken to evaluate their effectiveness and reliability. Thirty such facilities were identified in the United States and Canada. Four plants were selected for detailed study. The PhoStrip process is used at Lansdale, Pennsylvania and Savage, Maryland and operationally modified activated sludge processes are used in Lake Buena Vista, Florida and DePere, Wisconsin. These four facilities were found to be capable of achieving effluent total phosphorus concentrations of 1 mg/L or less without tertiary treatment.		
17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES 58
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

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INTRODUCTION

Eutrophication causes major problems in surface water bodies. Among its negative effects are depletion of dissolved oxygen (DO), limitation of recreational uses, and deterioration of aesthetic resources. Eutrophication can also cause taste and odor problems in water supplies. Municipal wastewater effluent containing phosphorus accelerates eutrophication in receiving waters where phosphorus is the limiting nutrient. For this reason wastewater effluent phosphorus control is important in many regions.

The degree of phosphorus control depends on the characteristics of the specific drainage area, regulations in individual states, and local receiving water conditions. Some areas face stringent effluent limitations. For example, 390 municipal wastewater dischargers to the Great Lakes who exceed a flow of 3,785 cubic meters per day (m^3/d) [one million gallons per day (mgd)] must meet a total phosphorus (TP) limitation of one milligram per liter (mg/l).¹ Effective phosphorus removal is an important consideration for these and other dischargers who must comply with strict phosphorus limitations.

In 1984, the U.S. Environmental Protection Agency sponsored a study to evaluate the effectiveness and reliability of biological phosphorus (Bio-P) removal processes. This study focused on field investigations at four full-scale wastewater treatment plants. Bio-P removal depends on microorganisms to remove phosphorus. Key objectives of the evaluation were: (1) to obtain information about the design, operation, and performance of Bio-P removal technologies; (2) to document achievable effluent phosphorus concentrations; and (3) to compare performance characteristics of the technologies investigated based on full-scale operating experience. The study began in the spring of 1984 and continued until August 1985.

Bio-P Removal Facility Inventory

One of the first tasks was to take an inventory of full-scale Bio-P removal facilities in the United States and Canada. Table 1 presents a summary of these facilities identified as of April 1984.²

Twenty-eight of the thirty facilities currently in operation, construction, or design use three proprietary processes - PhoStrip, A/O, and Modified Bardenpho. In April 1984, five of eleven plants in full-scale operation used PhoStrip, one was an A/O plant, and three were Modified Bardenpho plants. Two operationally modified activated sludge plants were also identified. Two of Bio-P removal plants are privately owned; the remainder are municipally owned wastewater treatment plants. Two PhoStrip and two operationally modified activated sludge plants were selected for detailed investigation during the technology evaluation. One of the operationally modified activated sludge plants uses an initial anoxic tank followed by a completely mixed aeration basin. The other uses a plug flow basin with an initial anaerobic zone. Operational modifications employed at these plants involved shutting off the air supply in the initial stage of the aeration basins to provide an anaerobic or anoxic zone. Neither facility was designed for Bio-P removal.

BIO-P REMOVAL TECHNOLOGIES

All full-scale applications of Bio-P removal technologies are modifications of the activated sludge process. These processes employ either an anaerobic or anoxic^a contact period in a cyclic mode

^aIn this paper, anaerobic conditions are operationally defined as an environment containing less than 0.2 mg/l of both DO and oxidized nitrogen. Anoxic conditions are operationally defined as an environment containing less than 0.2 mg/l of DO, but greater than 0.2 mg/l oxidized nitrogen.

Table 1 Summary of Full-Scale Bio-P Removal Facilities in the U.S. and Canada, Spring 1984

Bio-P removal process	Characteristics		
	Total number	Operating	Under design/construction
PhoStrip ^a	10 ^b	5	5
A/O ^c	10	1	9
Modified Bardenpho ^d	8	3	5
Operationally modified activated sludge ^e	2	2	-
Total	30	11	19

^aBioSpherics Incorporated.

^bThree other PhoStrip facilities have been shut down: two due to mechanical problems, the other because the phosphorus limitation was rescinded.

^cAir Products and Chemicals, Inc.

^dEIMCO Division of Envirotech Corporation.

^eConventional activated sludge systems operationally modified to provide an anaerobic or anoxic zone prior to aeration.

to select for microorganisms that reduce effluent phosphorus levels through "luxury" uptake and storage. As the process schematics presented on Figure 1 show, the A/O (anaerobic/oxic), Modified Bardenpho, and operationally modified activated sludge processes are mainstream processes that remove phosphorus in the waste activated sludge. PhoStrip is a sidestream process that combines biological and chemical phosphorus removal. With PhoStrip, a return activated sludge sidestream containing 10 to 30 percent of the mainstream flow is treated for chemical precipitation of a phosphorus-rich supernatant.³ Since lime dosage mainly depends on the alkalinity of the water stream, there is a significant reduction in chemical usage over mainstream chemical precipitation processes because only a small portion of the waste stream requires treatment. All of the processes can be adapted for combined phosphorus and nitrogen removal.

Process Descriptions

Full-scale sidestream and mainstream Bio-P removal processes are described below. Table 2 shows typical design criteria for these processes.

PhoStrip Process. Key features of the PhoStrip process are the anaerobic stripper tank and the lime reactor clarifier (Figure 1a). Sludge is retained in the stripper, which acts like a gravity thickener, for a period equivalent to a solids detention time (SDT)^b of 5 to 20 hours. There, biologically bound phosphorus is released from the sludge blanket into solution. The soluble phosphorus is transferred to the stripper supernatant either by recycling stripper underflow to the stripper feed, or by elutriation. The elutriant can be primary, secondary, or reactor clarifier effluent. Treatment with

^bSDT is defined as the mass of solids in the stripper blanket divided by the mass of solids leaving the system in the underflow per day. Stripper solids are estimated from the sludge blanket depth and underflow solids concentration.

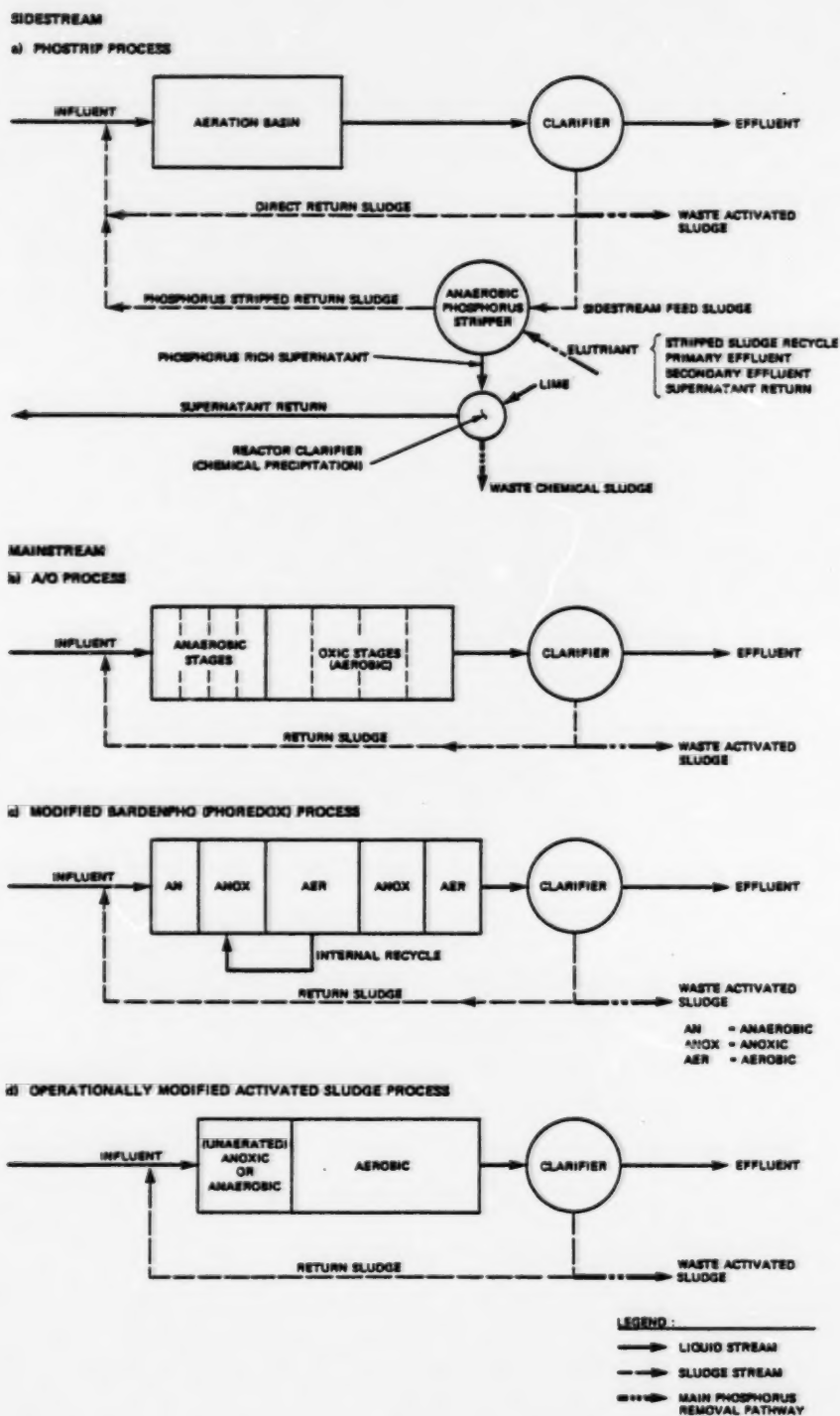


Figure 1 Schematics of Bio-P Removal Processes

Table 2 Summary of Recommended Design Criteria for Bio-P Removal Processes

PhoStrip ^a		A/O ^b		Modified ^c Bardenpho	
Criterion	Value	Criterion	Value	Criterion	Value
Activated Sludge System				Influent COD/TKN	> 10
F/M, kg BOD ₅ /kg MLVSS-day	-- ^d	F/M _s , kg SBOD ₅ /kg MLVSS-day	0.4-0.8	F/M, kg BOD ₅ /kg MLVSS-day	0.1-0.4
MLSS, mg/l	600-5,000	MLSS, mg/l	3,200-4,200	MLSS, mg/l	2,000-3,000
HRT, hour ^e	1-10	HRT, hour ^e		HRT, hour ^{e, g}	
PhoStrip Stripper		Anaerobic	0.75-1.5	Anaerobic	1-2
Feed, flow percent of mainstream flow	20-30	Oxic	2.0-3.0	Anoxic 1	2-4
		Return sludge, percent of mainstream flow	25-40	Aerobic 1	3-8
SDT, hours	5-20 ^f			Anoxic 2	2-4
				Aerobic 2	0.5-1
Side water depth, m(ft)	6.1 (20)			Return sludge, percent of mainstream flow	100
Elutriation flow, percent of stripper feed flow	50-100			Internal recycle, percent of mainstream flow	400
Underflow, percent of mainstream flow	10-20				
Overflow, percent of mainstream flow	10-20				
Reactor Clarifier					
Overflow rate, m ³ /m ² -day (gpd/sf)	49 (1,200)				
pH	9-9.5				
Lime dosage, mg/l	100-300				

^aReference 3.^bReferences 4 and 5.^cReference 5.^dBased on activated sludge mode.^eNominal hydraulic residence time.^fBased on mass of solids in stripper.^gActual design based on nitrification/denitrification kinetic constants. Typical values are presented here.

lime in the reactor clarifier causes the phosphorus in the stripper supernatant to precipitate. Underflow, stripped of phosphorus, is then returned to the aeration basin where biological phosphorus uptake occurs.

A/O Process. The key feature of the A/O process is the anaerobic contact tank with a nominal hydraulic residence time (HRT)^C of 0.75 to 1.5 hours.⁴ The A/O process is a high-rate activated sludge system with a mean cell residence time (MCRT) of 2 to 5 days. The system uses a series of completely mixed tanks to separate anaerobic and aerobic zones and to simulate plug flow conditions (Figure 1b). High sludge production enhances phosphorus removal and yields biomass containing up to 6 percent phosphorus on a dry weight basis.⁵ Aerobic sludge-handling processes normally are required to limit release and recycle of phosphorus back to the system. Best performance occurs when the influent soluble 5-day biochemical oxygen demand to soluble phosphorus ratio (SBOD₅/SP) exceeds 10.⁶

Modified Bardenpho Process. As Figure 1c shows, the Modified Bardenpho Process uses an initial anaerobic tank in series with anoxic and aerobic tanks. Return sludge is mixed with influent wastewater in the initial anaerobic tank to induce phosphorus release. The basic concept was described by Barnard^{7,8} to provide for single sludge denitrification by recycling nitrified aerobic basin effluent back to an anoxic zone. The second set of anoxic/aerobic tanks polishes wastewater for residual nitrate removal and aerates effluent before secondary clarification.

The Modified Bardenpho process uses an initial anaerobic tank ahead of the anoxic tank because oxidized nitrogen (NO_x-N) inhibits Bio-P removal. Typical MCRT values are 6 to 15 days to allow for

^CIn this paper, HRT is defined as the forward flow divided by the basin volume. Contact time is defined as the actual HRT or the total flow (forward plus recycle flows) divided by the basin volume.

nitrification and denitrification. The sludge solids are stable at these high MCRT values, and require little additional conditioning except for pathogen destruction. This process operates best when the influent BOD_5/TP ratio is greater than 20, and when the influent chemical oxygen demand to total Kjeldahl nitrogen ratio (COD/TKN) is greater than 10 or the BOD_5/TKN ratio is greater than 4.³ Process design is based on kinetic constants required for nitrogen oxidation and removal.

Operationally Modified Activated Sludge Process. The key feature of this Bio-P removal process is the development of an initial anoxic or anaerobic stage in an operating activated sludge system. Influent wastewater and recycled sludge are mixed in this zone to induce phosphorus release before aeration (see Figure 1d). Typically, the process uses a relatively short MCRT of less than 6 days. The initial applications of this concept occurred at San Antonio,⁹ Los Angeles,¹⁰ and Baltimore¹¹ during the late 1960s and early 1970s. These conventional activated sludge plants recorded high phosphorus removals, largely by happenstance. The plants employed long plug flow reactors, graduated aeration from inlet to outlet, and short MCRTs of 1-1/2 to 6 days. Operators observed phosphorus release in the front end of the basins. Though not known at that time, heavy organic loadings and inadequate aeration were causing anaerobic conditions, which, in turn, caused phosphorus release.¹² One plant studied as part of this evaluation uses a plug flow basin; the other plant uses separate, completely mixed anoxic and aerobic basins for effective phosphorus removal and operates at a 10-day MCRT.

Phosphorus Removal Mechanism

Bio-P removal processes depend on a population of microorganisms that accumulate more phosphorus than is typically found in activated sludge biomass. Measurements of biomass as total suspended solids (TSS) containing up to 7 percent phosphorus on a dry weight basis have been recorded for Bio-P removal process sludges. For conven-

tional activated sludge, biomass with 1.5 to 3 percent phosphorus is typical. Several conditions are necessary for this "luxury" uptake to occur. These include (1) anaerobic-aerobic staging,⁸ (2) phosphorus release in one anaerobic stage in the presence of a readily biodegradable organic substrate that is simultaneously absorbed during this stage,¹⁴ and (3) rapid soluble phosphorus (SP) uptake in the aerobic basin by polyphosphate (poly-P) accumulating microorganisms.

Marais¹² postulated a population selection theory to explain the presence of these organisms in the activated sludge biomass of mainstream processes. According to this theory, poly-P accumulation serves as an energy reservoir to sustain the organisms during the anaerobic stressed state. In the anaerobic stage, these organisms gain an advantage over nonpoly-P accumulating organisms by absorbing the organic substrate in the anaerobic basin for their exclusive use. Little soluble organic substrate enters the aerobic zone for the nonpoly-P accumulating aerobic organisms to effectively compete with the poly-P accumulating organisms.

It is not known yet if there are significant differences in the phosphorus accumulation mechanism between mainstream and sidestream processes. Unlike mainstream processes, it appears that in the PhoStrip process low molecular weight organics in the sidestream anaerobic reactor are formed by hydrolyzation of particular organics and from lysed bacteria during the long SDT.¹³ If so, phosphorus release in the PhoStrip stripper comes from both poly-P accumulating microorganisms and lysed bacteria.

In mainstream processes, a nominal anaerobic contact period of 1 to 2 hours is generally used to select for these poly-P accumulating microorganisms.⁷ A SDT of 5 to 20 hours is used in the PhoStrip process. The presence of $\text{NO}_x\text{-N}$ or DO in the anaerobic reactor inhibits phosphorus release.⁸ This reduced phosphorus release limits phosphorus uptake in the aerobic reactor and has a negative effect on

Bio-P process performance. Levels of DO above 2 mg/l have been noted as necessary for effective phosphorus uptake in the aerobic basin, with concentrations above 4 mg/l resulting in no significant increase in phosphorus uptake.^{11,13,15}

Arvin¹⁶ has identified another factor contributing to improved Bio-P process performance: simultaneous chemical precipitation of phosphorus caused by cations in the wastewater. Under anaerobic conditions, phosphorus release increases the driving force for phosphate precipitation at pH values above 7. Denitrification can also occur within microfilms, causing an increase in pH levels and creating microenvironments conducive to phosphorus precipitation.

Effluent Phosphorus Characteristics

Bio-P removal is analogous to BOD₅ removal in that the process converts soluble phosphorus to a suspended form (biomass) in the aeration basin. Thus, for effective treatment, the suspended biomass must be removed. To illustrate, for an effluent SP concentration of 0.7 mg/l, a suspended phosphorus concentration of 0.3 mg/l is required to achieve an effluent TP concentration of 1.0 mg/l. Figure 2 shows the relationship between effluent TSS, phosphorus content of the TSS, and suspended phosphorus concentration for effluent TSS concentrations between 0 and 30 mg/l. If effluent TSS contain 5 percent phosphorus, an effluent TSS concentration of 6 mg/l or less would be required to achieve this level of treatment. At a 3 percent phosphorus content, a 10 mg/l TSS concentration would be required. The relationship between effluent TSS, biomass phosphorus content, and soluble phosphorus residual is therefore important in defining achievable effluent phosphorus levels for the Bio-P removal technologies.

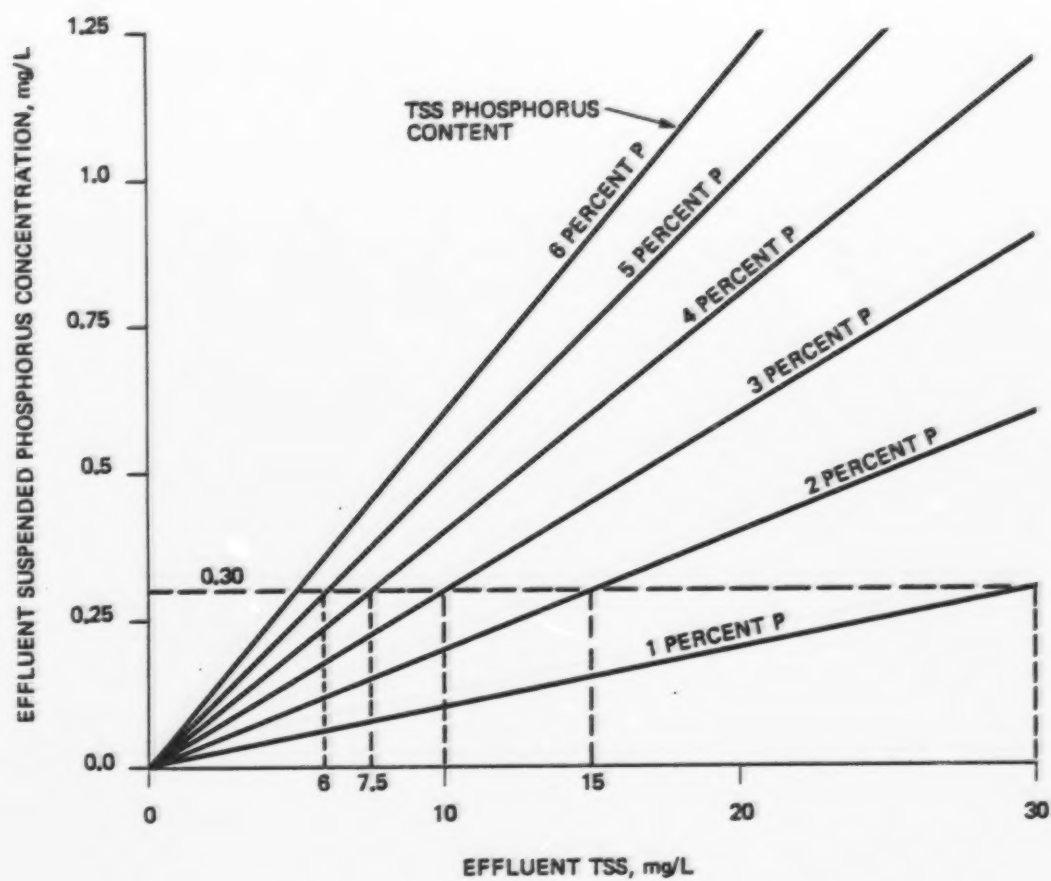


Figure 2 Effect of TSS Phosphorus Content on Effluent Suspended Phosphorous Concentration

FULL-SCALE INVESTIGATIONS

Investigations conducted at four full-scale Bio-P removal plants provide the basis for the technology evaluation. Descriptions of the methodology and of each plant are presented below, along with the results of the investigation.

Methodology

The evaluation focused on the sidestream PhoStrip process and mainstream anaerobic/aerobic and anoxic/aerobic operating modifications to the activated sludge process. Operating A/O and Bardenpho plants were not available for detailed investigation, so these processes are not included directly in this evaluation. However, selected published information on the performance of full-scale A/O and Bardenpho plants is included for comparison to results from the on-site investigations.

The plants selected for study of the PhoStrip process were the Lansdale Wastewater Treatment Plant (Lansdale WWTP), Lansdale, Pennsylvania, and the Little Patuxent Wastewater Treatment Plant (Little Patuxent WWTP), Savage, Maryland. For the operationally modified activated sludge processes, the plants selected were the Reedy Creek Improvement District Main Wastewater Treatment Plant (Reedy Creek WWTP) in Lake Buena Vista, Florida, and the DePere, Wisconsin, Wastewater Treatment Plant (DePere WWTP).

Plant selection was based on historical performance and availability of routine monitoring data, mass balance information, plant personnel, and laboratory resources. The investigations consisted of (1) a review of facility planning and background information, (2) collection of historical operating and performance data, and (3) independent testing and analysis at each location to study specific aspects of the Bio-P removal process. An analytical quality control

program was implemented to ensure consistent reporting of results from each plant. Table 3 shows the methods of analysis.^{17,18} The two PhoStrip plants use filtrable ortho phosphorus (OP) as the measure of soluble phosphorus. The operationally modified activated sludge plants measure SP using the standard filtrable phosphorus procedure that includes a digestion step to reduce soluble poly-P to soluble ortho phosphorus. SP is defined as the phosphorus filtrable through 0.45 micrometer pore size membrane filter in accordance with Standard Methods. The actual SP concentration at the PhoStrip plants lies between the TP and OP concentrations because poly-P in the soluble form is not detected by the analysis for OP. However, in this paper, OP is considered to constitute the soluble phosphorus fraction.

The study team developed and conducted sampling programs over a 4- to 9-week period at each plant during June, July, and August 1984. The sampling programs emphasized evaluation of the Bio-P removal processes, but included other unit operations and processes where appropriate. Objectives were to define: (1) process operating conditions; (2) achievable effluent phosphorus concentrations; (3) a representative phosphorus mass balance; (4) effects of nitrification and denitrification; (5) effects of the Bio-P removal processes on activated sludge settling characteristics; (6) impacts of solids handling operations; and (7) relative phosphorus removals by chemical and biological methods in the PhoStrip process. The team also identified key operating problems at each plant and documented the methods used to resolve these problems.

Key Plant Features

Table 4 presents the unit processes and operations used at each wastewater treatment plant (WWTP) studied. Figure 3 shows flow schematics for each plant.

Table 3 Methods of Analysis

Measurement parameter	Reference ^a
Solids (residues)	
Total	209A
Total suspended	209D
Volatile suspended	209E
Phosphorus	
Total (P)	424C, F, G
Filtrable (SP) ^b	424A, B, F, G
Filtrable Ortho (OP) ^b	424A, F, G
Nitrogen	
Ammonia (I)	417A, B
Ammonia (II)	417A, D
TKN	420; 417D
Nitrate	EPA 325.1 ^c
Nitrate plus nitrite (I)	418E, 419
Nitrate plus nitrite (II)	418C
Biochemical oxygen demand	507

^aMethods are from Reference 17 unless otherwise indicated.

^bFiltered through a 0.45 micrometer pore size membrane filter.

^cReference 18.

Table 4 Summary of Wastewater Plant Unit Processes and Operations

Wastewater treatment plant	Unit process and/or operation ^a			
	Prephosphorus removal	Phosphorus removal ^b	Postphosphorus removal	Sludge handling
Lansdale	Barscreening Comminution Grit Removal On-line equalization	Plug-flow activated sludge PhoStrip	Nitrification trickling filters/ clarification Suspended growth denitrification/post aeration/clarifica- tion Chlorination/ dechlorination	Gravity thickeners w/lime stabilization Vacuum filtration off-site disposal or liquid sludge spreading
Little Patuxent	Bar screening Grit removal Off-line flow equalization Primary clarification	Step-feed activated sludge (July 1984) Plug flow activated sludge (April 1985) PhoStrip	Suspended growth nitrification/ clarification Coagulation/ flocculation Filtration ^c Chlorination/ dechlorination and postaeration	Aerobic digestion (biological sludges) Gravity thickening with chemical sludge Filter press dewatering Off-site disposal
Reedy Creek	Comminution Grit removal (aerated only) Primary sedimentation	Plug flow activated sludge Anaerobic/aerobic zones	Chlorination Wetlands treatment	Dissolved air flotation (waste activated sludge) Aerobic digestion primary and thickening waste activated sludges)
DePere	Grit removal	Completely mixed activated sludge Anoxic tank/aerobic tank in series	Multimedia filtration ^c Chlorination	Land spreading Dissolved air flotation Sludge storage Plate frame filter press dewatering Incineration

^aIncludes only unit processes and operations in service during the field investigations.^bRefer to Figure 1.^cTertiary phosphorus removal processes.

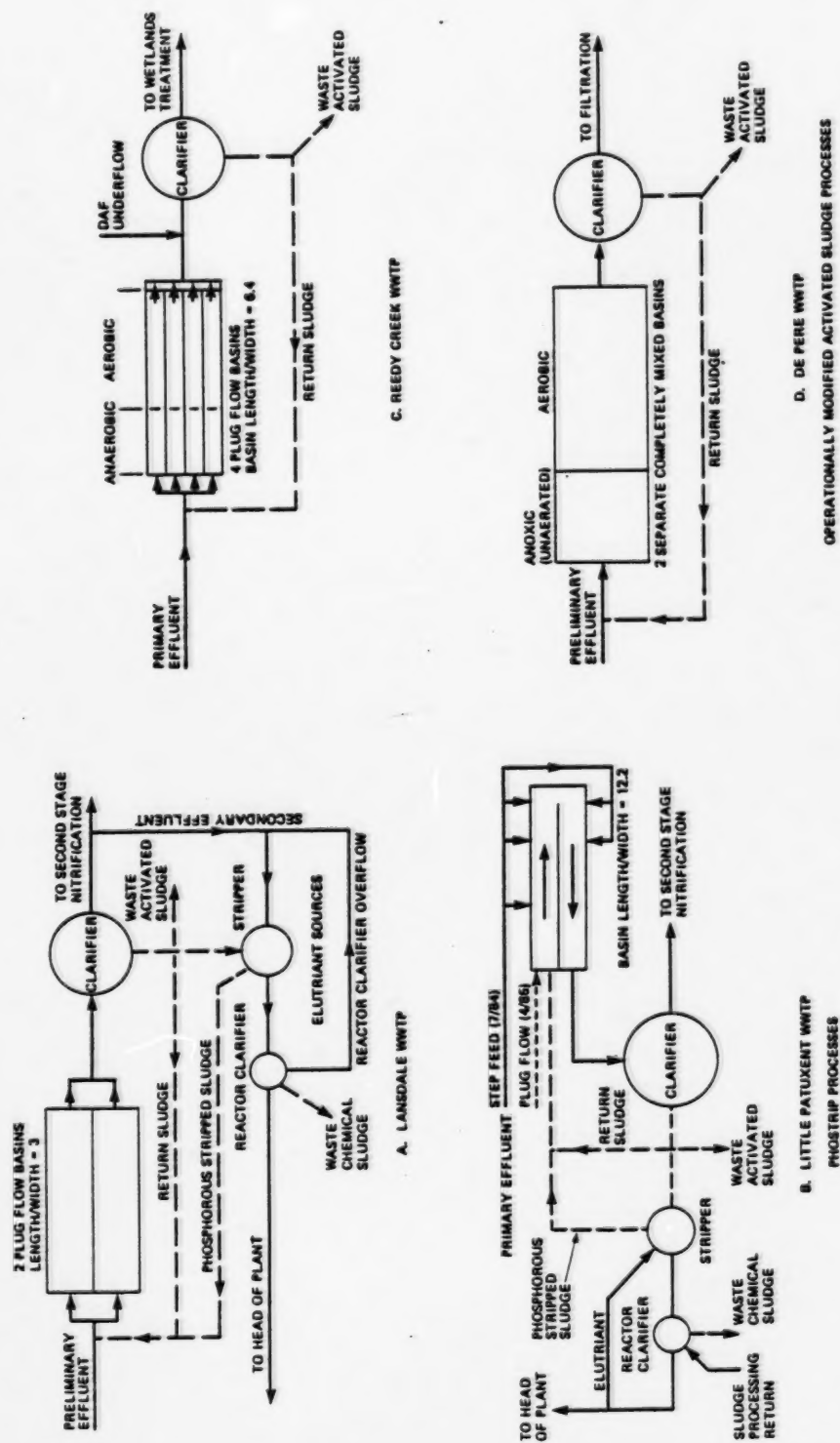


Figure 3 Flow Schematic for the Bio-P Removal Process at Each Plant Studied

The 9,450 m³/d (2.5 mgd) Lansdale WWTP uses the PhoStrip process. There is no primary treatment at this facility; however, flow is equalized in an on-line basin with a 24-hour HRT. After preliminary treatment, wastewater flows to the activated sludge-PhoStrip system (Figure 3a) for BOD₅ and phosphorus removal. Reactor clarifier overflow and secondary effluent are used to elutriate phosphorus in the stripper. Nitrification occurs in the activated sludge process with full nitrification occurring during the summer months. Separate-stage nitrification and denitrification are also used. Waste biological sludges are combined with the waste chemical sludge from the PhoStrip process, gravity thickened, stabilized with lime, and then dewatered or spread on land.

The Little Patuxent WWTP, a 56,800-m³/d (15 mgd) plant, also uses the PhoStrip process with a high-rate activated sludge process (Figure 3b). Additional treatment facilities include primary sedimentation, separate-stage nitrification, chemical coagulation/flocculation, and filtration for residual TSS and phosphorus removal (see Table 4). Partial nitrification occurs in the first-stage activated sludge system. Reactor clarifier overflow is used as an elutriant in the stripper. During the field investigation, the activated sludge system was operated in a step-feed mode. However, in November 1984, the process was converted to plug flow operation to improve phosphorus uptake. Operating changes in the PhoStrip process were also implemented at this time. Primary and waste biological sludges are aerobically digested before gravity thickening with the waste chemical sludge. Thickened sludge is dewatered by belt filter presses before final disposal.

The 22,700 m³/d (6.0 mgd) Reedy Creek WWTP serves the Walt Disney World Complex. Primary effluent is combined with return sludge and distributed to four parallel plug flow basins (Figure 3c). The initial third of each basin is unaerated, resulting in DO and NO_x-N concentrations less than 0.2 mg/l. Back mixing provides sufficient agitation to maintain solids in suspension in the unaerated zone.

Nitrification and denitrification also occur in this single-sludge system. Waste activated sludge is thickened by dissolved air flotation (DAF), and combined with primary sludge for aerobic digestion. Digested sludge is spread on land.

The 53,750 m³/d (14.2 mgd) DePere WWTP employs a converted contact-stabilization activated sludge system. Operators have shut off air flow to the stabilization tank to provide an initial anoxic basin for phosphorus release before treatment in a completely mixed aeration basin (contact tank) for BOD₅ and phosphorus removal, and nitrification (see Figure 3d). Because the system is operated to nitrify, recycle of NO_x-N in the return sludge creates anoxic conditions in the initial tank. Mixing in this basin is accomplished by turbine aerators without air. This plant has no primary treatment; raw wastewater is degrittied and aerated before secondary treatment. Waste activated sludge is thickened in DAF units and stored. Periodically, stored waste sludge is chemically conditioned, dewatered in a plate and frame filter press, and incinerated.

Table 5 summarizes phosphorus and BOD₅ concentrations influent to the Bio-P removal process at each plant during the field investigations. In this table, and throughout this paper, data for July 1984 and April 1985 are presented for the Little Patuxent WWTP. A comparison of these two sets of data shows the effects of the operational changes made in November 1984 that improved performance. Data for the July 1984 period are based on the monthly operating reports and results from special studies conducted as part of the field investigation. Data for the April 1985 period are based only on monthly operating reports. These data typify performance achieved for a 6-month period beginning in November 1984. Approximately 20 percent TP removal occurred through preliminary and/or primary treatment processes. As Table 5 shows, the plants operated below design hydraulic loadings during the field investigation periods.

Table 5 Summary of Phosphorus and BOD₅ Concentrations During Field Investigations

Plant	Flow		Raw Wastewater TP concentration, mg/l	Process influent concentration, mg/l ^a				
	m ³ /d(mgd)	Percent of design		TP	SP	OP	BOD ₅	SBOD ₅
Lansdale	8,350(2.2)	88	6.4	5.4	—	3.1	41 ^e	—
Little Patuxent								
July 1984	47,300(12.5)	83	8.2	6.6	—	3.7	103	38
April 1985 ^d	40,880(10.8)	72	8.8	7.0	—	4.8	92	—
Reedy Creek	18,150(4.8)	80	— ^b	6.7	5.3	—	155	85
DePere	13,250(3.5)	49 ^c	6.4	5.1	1.9	—	150	86

^aProcess influent is primary effluent at the Little Patuxent and Reedy Creek WWTPs. The Lansdale WWTP process influent is dewatered wastewater that is aerated and stored (equalized) for a nominal HRT of 24 hours prior to the Bio-P removal process. Process influent at the DePere WWTP is dewatered wastewater.

^bSampling error, TP concentration greater than 6.7 mg/l.

^cBased on only one parallel treatment train in operation.

^dFrom plant records.

^eInhibited BOD₅.

Treatment Effectiveness

Table 6 gives final and process effluent concentrations for BOD₅, TP, and SP or OP experienced during the study period. Suspended phosphorus concentrations are also included in Table 6, these values were calculated from the recorded TP and OP or SP concentrations. Refer to Figure 3 and Table 5 for a description of tertiary treatment processes. Except for the Little Patuxent WWTP's July 1984 secondary effluent TP concentration of 1.7 mg/l, all plants achieved better than 1 mg/l TP in both the Bio-P removal process and final effluents. As Table 6 shows, the Bio-P removal process effluent and final effluent quality, excluding nitrogen, was better than advanced secondary standards (BOD₅ <25, TSS <25, and TP <1). Final effluent quality was better than advanced waste treatment standards (BOD₅ <10, TSS <10 and TP <1). This degree of overall treatment performance was required to achieve the low effluent TP concentrations at these plants. Because phosphorus removal is associated with BOD₅ uptake in both the anaerobic (or anoxic) and aerobic basins, phosphorus removal is maximized for a certain set of operating conditions by maximizing BOD₅ removal. The low residual BOD₅ concentrations in the Bio-P process effluents, with all but one value below 8 mg/l, shows that these plants achieved greater than 90 percent BOD₅ removal.

Table 7 presents biological phosphorus removals per unit of BOD₅ removed in the Bio-P removal process along with overall unit phosphorus to BOD₅ removals, including that from chemical removal in the PhoStrip processes. These unit removals are based on the difference between influent BOD₅ and TP and effluent OP or SP concentrations and carbonaceous BOD₅ concentrations. Unit biological removals which represent the amount of phosphorus removed in the waste activated sludge for the PhoStrip processes were calculated from mass balances conducted during the field investigations.

Table 6 Summary of Performance During Field Investigations

Plant	Bio-P process effluent								Final Effluent ^a						Permit TP, mg/l
	Concentration, mg/l								Concentration, mg/l						Percent ^b TP Removal
	BOD ₅	TSS	TP	SP	OP	Susp ^c	Percent TP Removal		BOD ₅	TSS	TP	SP	OP	Susp ^c	
Lansdale	3	4	0.8	--	0.7	0.1	85		1	5	0.8 ^d	--	0.8	0.1	88
Little Patuxent July 1984	16	26	1.7	--	0.9	0.8	74		2	8	0.7 ^f	--	0.1	0.6	91
April 1985 ^g	6	11	0.5	--	0.1	0.4	93		2	4	0.3 ^h	--	0.1	0.2	97
Reedy Creek	3	13	0.9	0.4	--	0.5	82		2	2	0.6 ⁱ	--	--	--	91
DePere	7	7	0.3	0.1	--	0.2	94		3	2	0.3 ^l	0.3	--	0.1	95

^aRefer to Table 4 for post-Bio-P removal treatment processes.^bOverall TP removal based on raw wastewater concentration.^cSusp = suspended phosphorus, calculated by difference.^dAfter separate stage nitrification and denitrification.^eAs PO₄-P (0.07 mg/l as TP).^fAfter filtration.^gFrom plant records.^hAfter wetlands treatment.ⁱAfter filtration.

of sodium aluminate for chemical phosphorus removal.

Table 7 Phosphorus Removals per BOD₅ Removed

Plant	Process	Unit removal, mg phosphorus removed per mg BOD ₅ removed	
		Biological ^a	Overall ^b
Lansdale	PhoStrip	0.041	0.124
Little Patuxent July 1984 April 1985	PhoStrip	0.033	0.058 ^c
		0.033	0.078 ^c
Reedy Creek	Operationally modified activated sludge	0.041	-
DePere	Operationally modified activated sludge	0.034	-

^aRemoved in waste activated sludge.^bIncludes chemical phosphorus removal.^cBased on effluent filtered BOD₅.

Values between 0.04 and 0.08 mg phosphorus per mg BOD₅ (mg P/mg BOD₅) have been reported for mainstream Bio-P removal processes.¹³ These unit values indicate that enhancement was similar at each plant.

TSS concentrations that averaged below 15 mg/l (except for the July 1984 Little Patuxent TSS concentration of 26 mg/l), provided for low suspended phosphorus concentrations of 0.1 to 0.8 in the Bio-P removal process effluent. Final effluent suspended phosphorus concentrations ranged between 0.1 and 0.6 mg/l, while TSS concentrations ranged between 2 and 8 mg/l. TP removal through the Bio-P removal processes ranged between 74 and 94 percent, with suspended phosphorus accounting for more than 50 percent of the effluent TP concentration at the Little Patuxent and Reedy Creek plants. Average overall TP removal through the plants ranged between 88 and 97 percent.

The DePere WWTP and the Little Patuxent WWTP (in April 1985) met their respective permit limitations of 1.0 and 0.3 mg/l TP, respectively (see Table 6). Reedy Creek WWTP does not have a TP limitation, although phosphorus removal is performed in light of a potential TP effluent limit of 0.65 mg/l. The Lansdale WWTP was out of compliance with the strict permit limitation of 0.07 mg/l TP (0.2 mg/l PO₄); however, the plant can achieve an effluent TP concentration less than 1 mg/l, which is the limit set in a revised draft permit. The Little Patuxent WWTP was out of permit compliance of 0.3 mg/l TP for the entire 13-month historical review period ending in August 1984.

Table 8 presents nitrification and total nitrogen (TN) removal data for each of the plants. As the table shows, almost complete nitrification occurred through the Bio-P removal processes in all but the Little Patuxent WWTP, with average ammonia (NH₃-N) removals

Table 8 Secondary Effluent Nitrogen Oxidation and Removal Summary

Plant	Concentration, mg/l		Removal, percent	
	NH ₃ -N	TN	NH ₃ -N	TN
Lansdale	0.2	14.2	98	31
Little Patuxent				
July 1984	11.2	19.8	27	18
April 1985	9.5	21.0	44	14
Reedy Creek	0.7	5.8	97	83
DePere	1.4	8.6	89	67

of 89 to 98 percent. Average TN removals through the Bio-P removal processes ranged between 14 and 83 percent; based on mass balances conducted during the field investigation, 73 percent and 34 percent of the overall TN removal through the Reedy Creek and DePere WWTPs, respectively, was attributed to denitrification. The remaining TN removed was contained in the waste activated sludge. All plants except for the Little Patuxent WWTP were operated to nitrify. These results indicate that nitrification and nitrogen removal can occur simultaneously at these plants while they continue to achieve effluent TP concentrations less than 1 mg/l. However, Bio-P process effluent contained between 5.8 and 21.0 mg/l TN, indicating that reduction of both TP and TN to advanced treatment levels (i.e., 1 mg/l TP, 2 mg/l TN) were not achieved at these facilities without tertiary treatment for nitrogen removal.

Historical Performance Summary. Figure 4 presents a cumulative frequency plot of Bio-P removal process performance based on historical average monthly data collected from each plant as part of the technology evaluation. This performance is representative of secondary effluent quality achievable under optimum operating conditions.

The Lansdale WWTP performance is based on 14 months of PhoStrip operation. It does not include 7 months of operation during which the PhoStrip process was in a start-up mode or was shut down for maintenance; effluent TP concentrations greater than 2 mg/l occurred during these periods.

The Little Patuxent WWTP data is based on the improved performance period between November 1984 and April 1985 (six data points). During this period, process effluent TP concentrations averaged below 1.3 mg/l. Prior to this period, process effluent TP averaged 2.0 mg/l and ranged between 1.4 and 3.2 mg/l for the 13-month period ending in August 1984. Both effluent TP and OP concentrations are shown on Figure 4 for these two plants. Compari-

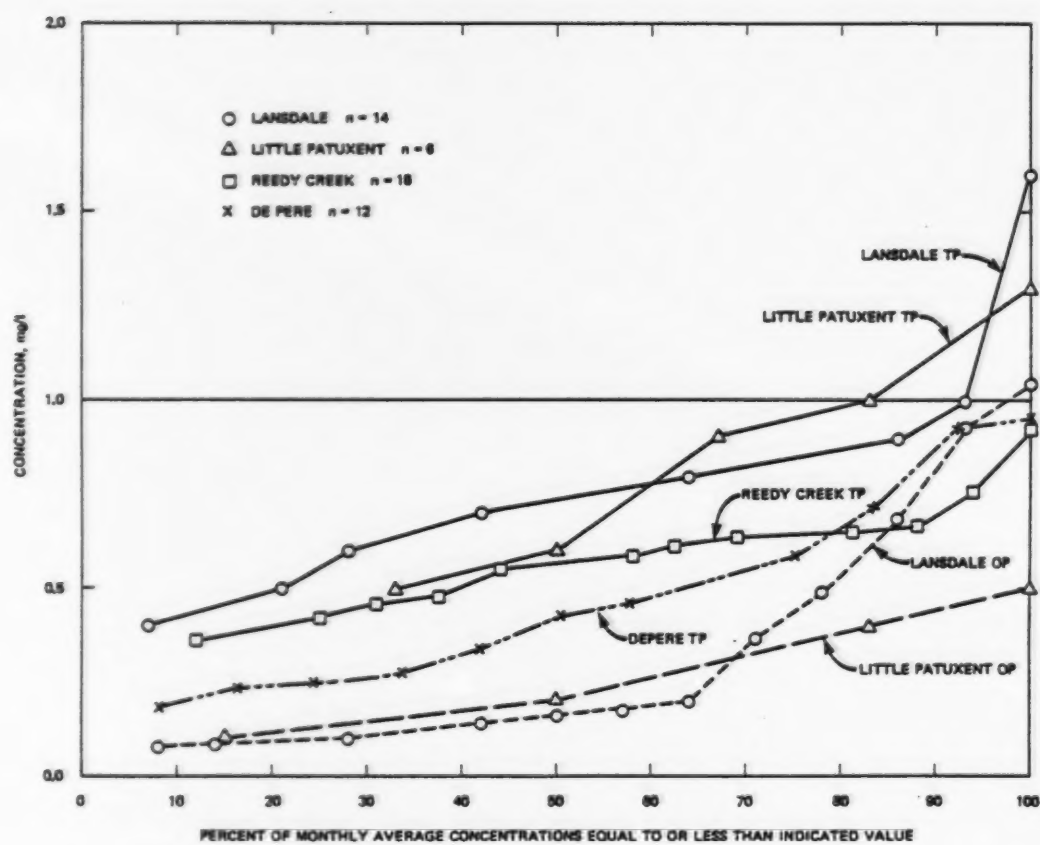


Figure 4 Bio-P Process Performance Reliability

son of the TP and OP performance curves for the respective PhoStrip plants shows that suspended phosphorus constitutes a significant portion of the effluent TP concentration. These results further show that the PhoStrip process produced an effluent containing less than 1 mg/l TP 83 to 93 percent of the time on a monthly basis, and OP concentrations below 0.5 mg/l 78 percent of the time.

TP data presented for the operationally modified Bio-P removal processes represent 16 and 12 months of operation for the Reedy Creek WWTP and the DePere WWTP, respectively. Effluent SP is not measured at these plants. At DePere, effluent TP is measured after multimedia filtration. After filtration, TSS concentrations are typically less than 1 mg/l; thus, virtually all suspended phosphorus is removed. Therefore, the TP in the filtered effluent is almost totally composed of SP. Effluent TP concentrations were below 1 mg/l 100 percent of the time and less than 0.65 mg/l 80 percent of the time for the operationally modified activated sludge processes. This historical performance analysis and the phosphorus removal performance experienced during the field investigations shows that the Bio-P removal processes can consistently and reliably achieve effluent TP concentrations of less than 1 mg/l without tertiary treatment.

Operating Conditions

Operating conditions have a significant effect on treatment performance. The following section covers key operating parameters during the study.

PhoStrip Plants. Table 9 summarizes operating conditions during the field investigations at the PhoStrip plants. The Lansdale WWTP stripper operated at a 20-hour SDT while the Little Patuxent WWTP stripper SDT was 7 to 8 hours. Testing performed during the field investigations indicated that the Lansdale stripper operated under anoxic conditions; nitrified secondary effluent used as an elutriant

Table 9 Summary of PhoStrip Plant Operating Conditions

Parameter	Plant and value		
	Lansdale	Little Patuxent	
		July 1984	April 1985
PhoStrip process			
Stripper			
SDT, hr	20	8	7
Feed flow, percent of mainstream flow	14	22	34
Elutriation flow, percent of feed flow	124	121	50
Elutriation rate, ^a l/g TSS-day	0.14	0.72	0.25
Underflow, percent of mainstream flow	10	14	21
Recycle, percent	0	0	78
Overflow, percent of mainstream flow	23	35	31
TP, mg/l	20.6	9.5	20.0
OP, mg/l	16.4	7.2	17.6
Reactor clarifier overflow			
TP, mg/l	3.6	3.9	7.2
OP, mg/l	0.9	0.9	1.2
Overflow rate, m ³ /m ² -day (gpd/sf)	65 (1600)	46 (1120)	34 (840)
Lime dosage, mg/l	100	160	100
pH	9.0	9.5	9.5
Activated sludge process			
F/M, kg BOD ₅ /kg MLVSS-day	0.16	0.5 ^{b,c}	0.5
MLSS, mg/l	1900	2950 ^b	2000
P/VSS, percent	3.3	4.0	4.6
MCRT, days	6.5	3.7 ^{b,c}	2.8
HRT, hrs	4.6	2.6	3.0
Return sludge recycle ratio	0.16	0.32	0.57
DO, mg/l	2-3	1.3	2-5
Sludge production, ^d kg VSS/kg BOD ₅	1.0	0.7	--

^aBased on mass of solids in stripper.^bEstimated from solids balance.^cCalculated based on estimated MLSS.^dBased on removed carbonaceous BOD₅.

cycled $\text{NO}_x\text{-N}$ to the stripper. Stripper overflow contained up to 3.6 mg/l $\text{NO}_x\text{-N}$. A DO profile conducted through the depth of the stripper showed that DO values increased from 0.15 mg/l at the bottom of the stripper sludge blanket to 0.5 mg/l at the top of the stripper. Measurements taken at the Little Patuxent WWTP in July 1984 showed that the stripper operated anaerobically with influent DO and $\text{NO}_x\text{-N}$ concentrations of less than 0.2 mg/l.

As Table 9 shows, different operational strategies were used at the two PhoStrip facilities. Total return sludge flows (direct return plus stripped sludge flows) to the activated sludge process averaged between 16 and 57 percent of the mainstream flows for the periods studied. Additionally, in April 1985, the Little Patuxent WWTP began to recycle stripper underflow to supplement reactor clarifier overflow used for elutriation. This operational change was implemented along with increased return sludge feed to the stripper. Under these conditions, the average stripper overflow TP concentration increased from 9.5 mg/l (July 1984) to 20.0 mg/l. Average lime dosage to the stripper overflow ranged between 100 and 160 mg/l at pH values between 9 and 9.5; 59 to 83 percent of the TP contained in the stripper overflow was removed in the chemical sludge.

The Lansdale WWTP activated sludge process operates at a low F/M, 0.16 kg $\text{BOD}_5/\text{kg MLVSS-day}$, while the Little Patuxent WWTP has a high F/M, 0.5 kg $\text{BOD}_5/\text{kg MLVSS-day}$. During the field investigation, the activated sludge system at the Little Patuxent WWTP was operated in the step-feed mode. This mode of operation, along with low DO levels (less than 2 mg/l) in the aeration basin limited the phosphorus uptake in the basin. Additionally, phosphorus release occurred in the secondary clarifiers; these factors resulted in poor process performance with an average TP concentration of 2.0 mg/l for the 13-month period noted earlier. In November 1984, plant personnel in consultation with BioSpherics Incorporated implemented the following operational improvements:

1. Operation of the activated sludge system in the plug flow mode (Figure 3b).
2. Increased DO levels in the aeration basin, up to 4 mg/l at the effluent end of the basin to improve phosphorus uptake in the basin and prevent phosphorus release in the secondary clarifiers.
3. Increased return sludge recycle ratio to maintain a minimum sludge blanket in the secondary clarifiers.

Chemical phosphorus removal in the PhoStrip process was also increased from 100 kg/d (221 lb/day) to 164 kg/d (361 lb/day). Unit biological phosphorus removal remained the same at 0.033 mg phosphorus/mg BOD₅.

Biological sludge production was 1.0 kilogram of volatile suspended solids per kilogram of BOD₅ removed (kg VSS/kg BOD₅) at the Lansdale WWTP and 0.7 kg VSS/kg BOD₅ at the Little Patuxent WWTP. Higher sludge production at the Lansdale WWTP, which does not provide primary sedimentation, was attributed to a higher nondegradeable VSS component in the preliminary treated effluent.

Both of the PhoStrip facilities have experienced lime scaling problems in the elutriation return piping system from the reactor clarifiers. When scaling occurs, the Lansdale WWTP temporarily substitutes ferric chloride and polymer for lime to precipitate phosphorus and to remove lime scale from the elutriation piping. The Little Patuxent WWTP shuts down one of the two stripper-reactor clarifier units and recarbonates the system on a batch basis to remove lime scale from the elutriation piping.

Modified Activated Sludge Facilities. Table 10 presents the operating conditions for the mainstream activated sludge process operated in the anaerobic/aerobic and anoxic/aerobic modes. The

Table 10 Summary of Operating Conditions at Operationally Modified Activated Sludge Plants

Parameter	Plant and value	
	Reedy Creek	DePere
Influent ratios		
BOD ₅ /TP	23	29
SBOD ₅ /SP	16	47
COD/TKN	11	--
BOD ₅ /TKN	4.7	5.8
HRT, hours		
Anaerobic	3.0	--
Anoxic	--	7.5
Aerobic	6.0	15.0
Contact period, ^a hours		
Anaerobic	1.9	--
Anoxic	--	3.8
Aerobic	3.8	7.6
Sludge, percent phosphorus	3.8	2.4
Activated Sludge System		
F/M, kg/BOD ₅ /kg MLVSS-d ^b	0.33	0.12
MLSS, mg/l	2100	3000
MCRT, days ^c	7.2	10.6
Return sludge recycle ratio	0.59	0.81
DO, mg/l	2-4 ^d	4
Sludge production, kg VSS/kg BOD ₅ ^e	0.7	0.9

^aBased on influent plus recycle flows (total flow).^bBased on aerobic basin volume only.^cBased on overall reactor(s) volume.^dEffluent end of basin.^eBased on removed carbonaceous BOD₅.

Reedy Creek WWTP operated at an F/M of 0.33 kg BOD₅/kg MLVSS-day, based on the biomass under aeration. The anaerobic contact period, based on influent plus sludge recycle flows, was 1.9 hours with an aerobic nominal hydraulic residence time (HRT) of 6 hours (influent flow only). The DePere WWTP was operated with an anoxic contact period of 3.8 hours at a low aeration basin F/M value of 0.12 kg BOD₅/kg MLVSS-day. NO_x-N concentrations in the anoxic basin ranged between 2 and 4 mg/l based on grab samples collected during the sampling program. The aerobic basin HRT was 14 hours, aerobic contact time was 7.6 hours. This long HRT is because the DePere plant is hydraulically loaded at only 50 percent of the design capacity. Both activated sludge systems were operated to nitrify with an MCRT of 7.2 days for the Reedy Creek WWTP and 10.6 days for the DePere WWTP.

Influent ratios for BOD₅/TP, SBOD₅/SP, COD/TKN, and BOD₅/TKN are also presented in Table 10. These values for both WWTPs are above the reported threshold values of 20, 10, 10, and 4 necessary to achieve low effluent phosphorus concentrations. These favorable wastewater characteristics are key factors in the process performance experienced at these plants. The high carbonaceous substrate to TP ratios indicate that sufficient substrate is available for the assimilation of phosphorus in the biomass, while the COD/TKN ratio is an empirical indication that there is sufficient substrate available for denitrification to occur in the anaerobic or anoxic reactors in excess of the substrate required during phosphorus release. Measurements of biological sludge indicated a phosphorus content of 3.8 and 2.4 percent on a dry weight basis for the Reedy Creek and DePere sludges, respectively. The Reedy Creek phosphorus content of 3.8 percent indicates that enhancement occurs in this system. The 2.4 percent phosphorus content of the DePere biomass is only marginally higher than conventional activated sludge. However, because the DePere WWTP does not provide primary treatment, biomass has a low volatile content which averages only 64 percent VSS. Because the phosphorus content of inerts is normally low, overall

phosphorus content of the sludge is reduced. On a VSS basis, a better indication of the active biomass, the DePere sludge contains 3.8 percent phosphorus while the Reedy Creek sludge contains 4.8 percent phosphorus.

Biological sludge production at the DePere WWTP was 0.9 kg VSS/kg BOD₅ removed while the Reedy Creek WWTP produced 0.7 kg VSS/kg BOD₅ removed. The DePere WWTP does not provide primary sedimentation, thus the high sludge production for the low F/M system (0.12 kg BOD₅/kg MLVSS-day) was attributed to a high nondegradable VSS component in the preliminary treated effluent. Prior to operationally modifying the activated sludge process for Bio-P removal at the DePere WWTP, chemicals were added to the activated sludge process to achieve effluent TP levels below 1 mg/l. Phosphorus removal performance has remained unchanged since conversion to the anoxic/aerobic Bio-P removal process. Prior to operation in the anaerobic/aerobic mode, the Reedy Creek WWTP typically achieved a secondary effluent TP concentration of 3 to 5 mg/l.

FACTORS AFFECTING PERFORMANCE

Before this study, the PhoStrip process had been described as the only Bio-P removal process capable of reliably achieving an effluent OP concentration less than 1 mg/l.^{3,5,15} The proprietary mainstream Bio-P removal processes (A/O and Modified Bardenpho) had been described as capable of achieving effluent OP concentrations of less than 2 mg/l, based primarily on performance at the Largo, Florida, A/O plant and the Palmetto, Florida, Modified Bardenpho plant.^{3,5,15}

The results of this investigation show that both the PhoStrip and mainstream operationally modified activated sludge process can

produce both effluent TP and OP or SP concentrations below 1 mg/l. This section covers the factors contributing to this performance for each of the Bio-P technologies.

PhoStrip Process

The PhoStrip process has significant operational flexibility because substantial phosphorus removal occurs through chemical precipitation, which is controlled by the stripper feed rate and other operating parameters. Phosphorus removal can occur at lower BOD₅/TP ratios than are necessary for mainstream processes that rely entirely on biological phosphorus removal. At too low a BOD₅/TP ratio there will be inadequate phosphorus uptake in the aeration basin. Several factors must be controlled to achieve an OP concentration below 1 mg/l. These factors are described below.

Stripper Operation. Key stripper operating and design parameters are the SDT, elutriation rate, and elutriant source. A sufficient SDT is required to release phosphorus in the stripper. Unlike mainstream Bio-P processes where readily degradable organics are present in the process influent, it appears that low molecular weight organics formed by hydrolysis of particulate organics from lysed bacteria are needed as substrate for phosphorus release to occur during the relatively long SDT of 5 to 20 hours.¹² When NO_x-N is present in the return sludge or elutriant streams, the SDT must be increased to allow for concurrent denitrification and phosphorus release to occur. Recommended design values for volumetric flows of stripper feed and elutriant have been presented in Table 2. Table 9 contains operating data from the field investigations; stripper feed ranged between 14 and 34 percent of the mainstream flow, which spans the recommended design range.

Comparison of the April 1985, Little Patuxent WWTP data with the Lansdale WWTP field investigation data (Table 9) shows that the two strippers attained approximately the same level of performance.

Overflows from both strippers contained approximately 20 mg/l TP and 17 mg/l OP. The Little Patuxent WWTP operated at a SDT of 8 hours under anaerobic conditions, and elutriation was accomplished by recirculation of the stripper feed (78 percent of the stripper feed flow) and reactor clarifier overflow (50 percent of the stripper feed flow). In contrast, the Lansdale WWTP used a combined elutriant flow (30 percent secondary effluent and 70 percent reactor clarifier overflow) that was 124 percent of the stripper feed flow. The anoxic SDT was 20 hours. Under these operating conditions, the elutriation rate was 0.25 l/g TSS-d based on the solids in the sludge blanket for the Little Patuxent WWTP, compared to 0.14 l/g TSS-d at the Lansdale WWTP. Thus, similar phosphorus release was achieved at the two facilities under quite different stripper operating conditions.

As Table 9 shows, stripper performance at the Little Patuxent WWTP in July 1984 was poor. It appears that the high elutriation rate of 0.72 l/g TSS-d was excessive for the rate at which OP was released to the elutriation stream. The reactor clarifier overflow was diluted to an OP concentration of 7.2 mg/l TP owing to the high elutriation flow and low SDT.

The choice of elutriant streams is important in the design and operation of the stripper. Reactor clarifier overflow and secondary effluent contain low phosphorus concentrations identified as necessary to elutriate the phosphorus released from the sludge blanket.³ In addition, these elutriant sources typically contain significant levels of DO and little organic substrate. When nitrification occurs in the activated sludge system, secondary effluent also contains $\text{NO}_x\text{-N}$. Under these conditions, an extended SDT is required to allow for lysing of cells used as a carbon source for both denitrification and phosphorus release; a 50 percent increase in SDT has been recommended for design.³ Typically, SDT can be varied over a wide range by adjusting the sludge blanket depth between 2 and 6 m (7 to 20 feet).

The PhoStrip system can remove nitrogen by denitrifying the nitrified secondary effluent that is used as an elutriant in the stripper. The Lansdale WWTP has operated in this manner.

Use of primary effluent as an elutriant provides a stream that contains significant concentrations of readily degradable organics that could increase phosphorus release. Under these conditions, a lower SDT could be used to achieve a specific stripper overflow phosphorus concentration. An extended SDT required to lyse cells for use as a substrate source would not be required. Therefore, there appears to be a need for a definitive study on the effects of waste stream characteristics on elutriation to determine whether increased operational flexibility could be provided by varying the elutriant characteristics and flows. Thus, various operating modes can be adopted in the activated sludge-PhoStrip system, depending on treatment performance objectives such as nitrification and denitrification as well as phosphorus removal.

Mass balance analysis performed for the activated sludge-PhoStrip systems showed that waste chemical sludge accounted for 67 percent of the overall TP removal at the Lansdale WWTP, with the remaining 33 percent accounted for in the waste activated sludge. During July 1984, only 42 percent of the TP removal at the Little Patuxent WWTP was accounted for in the waste chemical sludge. In April 1985, during the improved performance period, waste chemical sludge accounted for 58 percent of the TP removal. This result shows increased chemical phosphorus removal caused the improved performance.

Average mixed liquor suspended phosphorus to VSS (P/VSS) ratios ranged between 3.3 and 4.6 percent at the two PhoStrip plants. These values convert to 2.3 (Lansdale) and 3.9 percent (Little Patuxent) phosphorus on a TSS basis. The Lansdale WWTP has lower values

because two-thirds of the phosphorus was removed chemically at this plant, while less than 60 percent of the removed phosphorus at Little Patuxent was in the waste chemical sludge.

Typically, differences in P/VSS ratios between the stripped sludge and stripper feed were 0.3 to 0.6 percent. In a special study, investigators conducted a microbiological analysis of activated sludge mixed liquor and stripper underflow from the Lansdale WWTP, using Neisser staining techniques. The results showed significant reductions of intracellular polyphosphate granules in the stripped underflow as compared to quantities found in the mixed liquor. This finding confirms the release of phosphorus by microorganisms in the stripper and uptake of phosphorus by microorganisms in the aeration basin.

Mainstream Bio-P Removal Processes

Both operationally modified activated sludge plants and mainstream proprietary processes are capable of achieving effluent OP and SP concentrations below 1 mg/l.¹⁵ An A/O demonstration plant at Pontiac, Michigan, has consistently achieved an effluent TP concentration of less than 0.8 mg/l based on 12 months of operation.¹⁹ A modified Bardenpho plant serving Kelowna, British Columbia, Canada, has produced an effluent with a median OP concentration of 0.77 mg/l for a 2-year period ending in December 1984.²⁰ The plant was in compliance with the permitted TP limitation of 2.0 mg/l (after filtration) 90 percent of the time. However, Oldham noted that experiments, such as diverting all influent through one of the two modules, conducted at Kelowna plant with the Bio-P removal process negatively affected overall system performance²⁰.

The performance records at these plants and the field investigations at the two operationally modified activated sludge plants show that mainstream Bio-P processes can reliably achieve effluent OP and SP levels below 1 mg/l under certain operating

conditions. However, the Modified Bardenpho process has yet to demonstrate the ability to achieve effluent TP concentrations less than 1 mg/l 90 percent of the time. Several factors affect this performance.

Wastewater Characteristics. The BOD_5/TP (or $SBOD_5/SP$) ratio is the major parameter affecting wastewater treatability for mainstream Bio-P removal processes. Enhanced Bio-P removal requires that enough readily degradable organic substrate be available to permit phosphorus release under anaerobic conditions and subsequent uptake of phosphorus in the aerobic reactor. $SBOD_5$ is a better indicator of the amount of readily degradable organic substrate available than BOD_5 , so the $SBOD_5/SP$ ratio generally provides a better indicator of wastewater treatability for Bio-P removal. Figure 5 shows the effect of these parameters on effluent SP and OP concentrations. The figure includes data from literature citations and information obtained from a site visit to the Largo A/O plant as well as from this evaluation.

Typically, the anaerobic contact period employed at these facilities was on the order of 1/2 to 2 hours. However, the anoxic contact period at the DePere plant was 3.8 hours. This plant, with high influent BOD_5/TP and $SBOD_5/SP$ ratios of 29 and 47, respectively, achieved an average residual SP level of 0.1 mg/l during the 5-week field investigation. Based on the BOD_5/TP ratio for the facilities denoted on Figure 5, a value greater than 20 or 25 is necessary to consistently achieve an effluent OP or SP concentration of less than 1 mg/l. The threshold value for the $SBOD_5/SP$ ratio to meet the 1 mg/l SP criterion is 12 to 15. For BOD_5/TP and $SBOD_5/SP$ ratios below these values, OP and SP concentrations vary widely up to 4.5 mg/l.²¹

Figure 6 presents the relationship between influent $SBOD_5/SP$ and biomass phosphorus content on a dry weight (TSS) basis. As the figure shows, phosphorus content decreases with an increasing

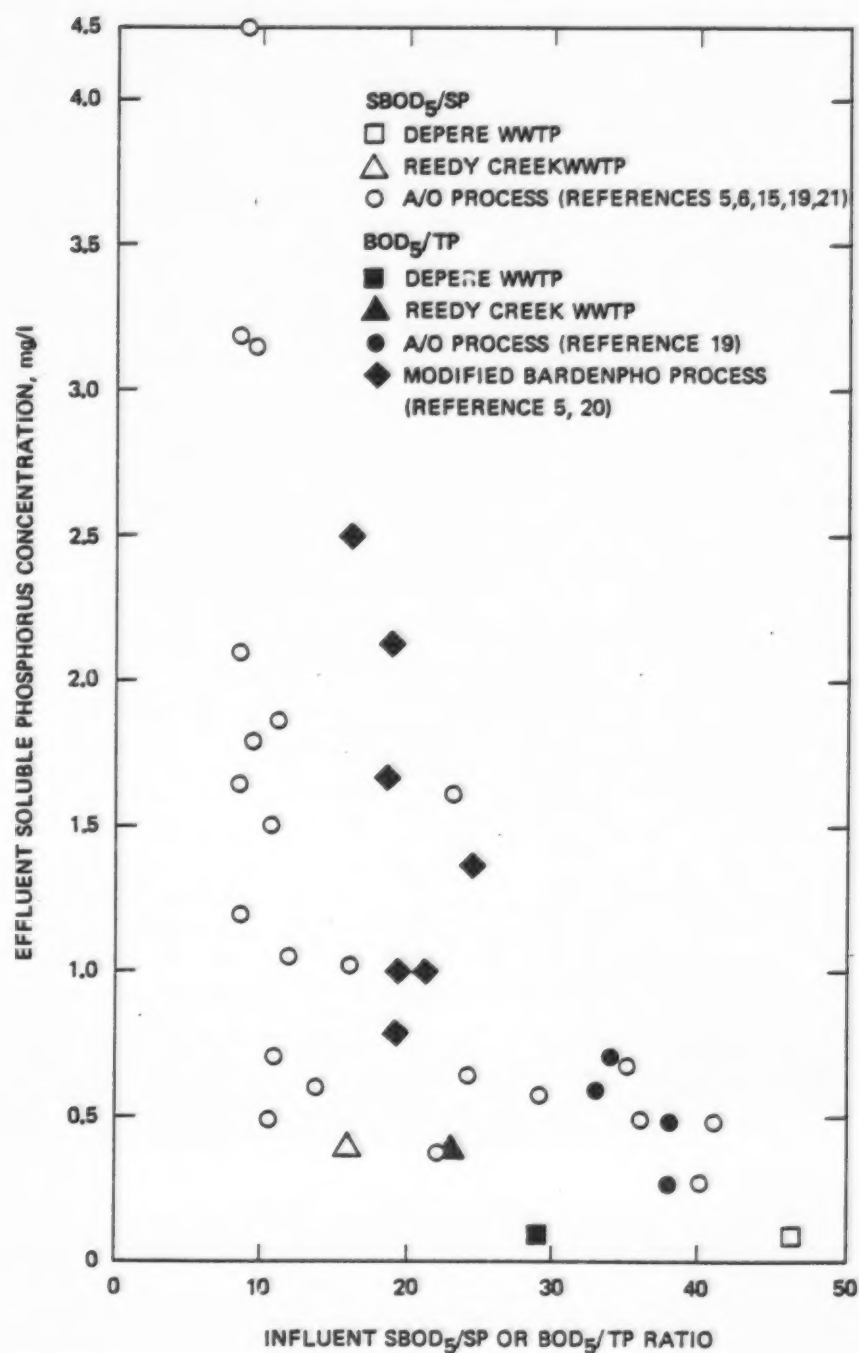


Figure 5 Relationship Between Influent BOD₅/TP, SBOD₅/SP Ratios, and Effluent Phosphorus Concentrations

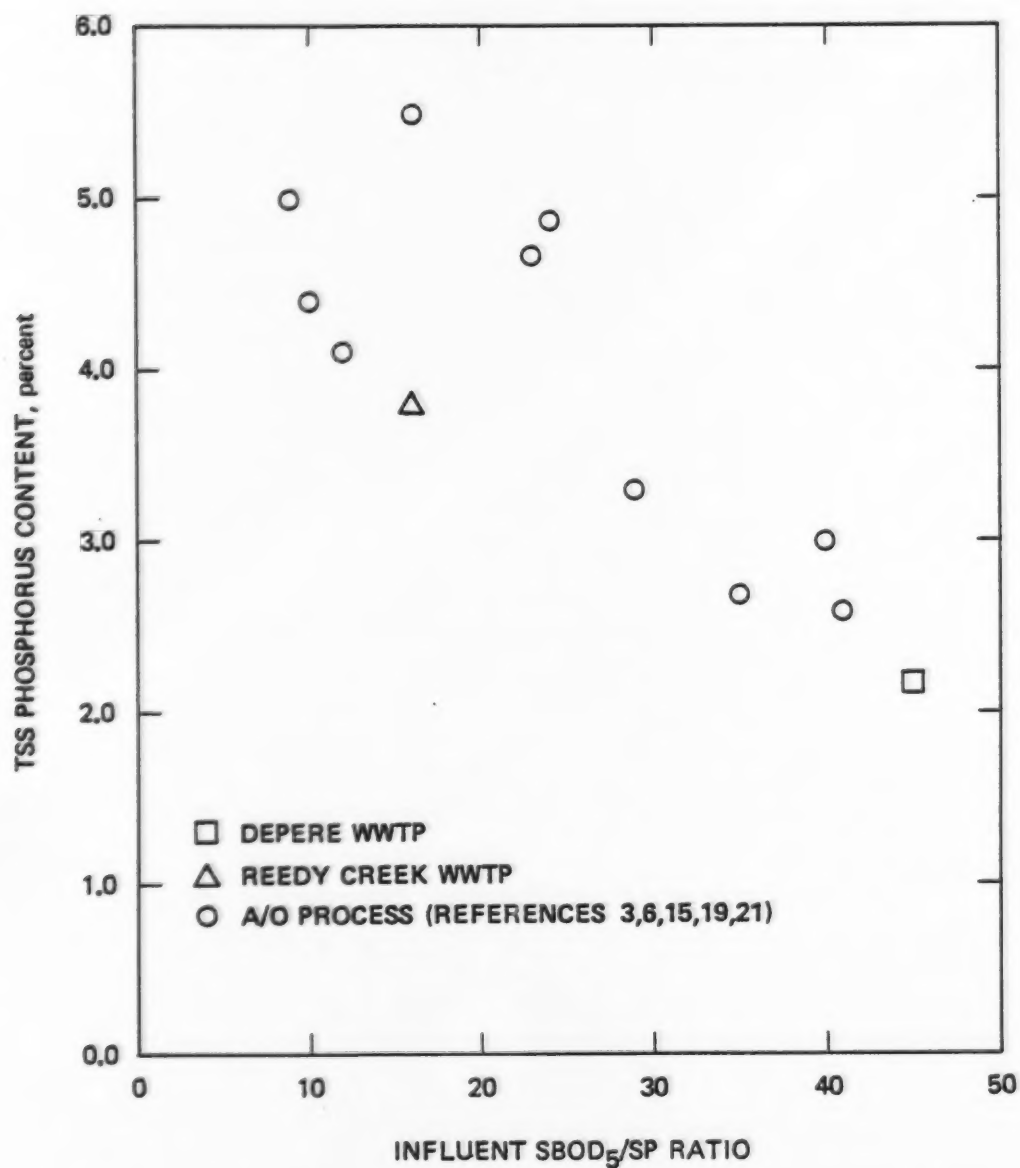


Figure 6 Effect of Influent SBOD₅/SP Ratio on TSS Phosphorus Content

SBOD₅/SP ratio because of the limited phosphorus available per unit of biomass. Therefore, Bio-P removal plants with high influent SBOD₅/SP values (>25) can achieve excellent process performance, producing low residual OP or SP concentrations and the associated low TSS phosphorus content. For example, compare these parameters for the two operationally modified activated sludge plants:

<u>Parameter</u>	<u>Reedy Creek</u>	<u>DePere</u>
SBOD ₅ /SP	16	47
Effluent SP, mg/l	0.4	0.1
TSS, percent TP	3.8	2.4
Effluent TP, mg/l	0.9	0.3
Effluent TSS, mg/l	13	7

The DePere WWTP with a very high SBOD₅/SP ratio has both low effluent SP and TSS percent phosphorus values, which would result in lower effluent TP concentrations if equal secondary clarifier performance was provided.

No standard definition exists for readily degradable organics. SBOD₅ is used because it is readily measurable with standard tests associated with the Bio-P removal processes. The process influent SBOD₅ fraction depends on the level of preliminary and primary treatment, as well as raw wastewater characteristics. As shown in Table 6, SBOD₅ constituted 37 to 55 percent of the BOD₅ in the Bio-P removal process influents. The Kelowna, B.C., Modified Bardenpho facility reported improved process performance when primary sludge thickener supernatant was used to supplement primary effluent as a source for readily degradable organics.¹⁷

Anaerobic/Anoxic Contact. The anaerobic contact period at the Reedy Creek WWTP was 1.9 hours during the field investigation. The anaerobic zone contains one-third of the volume of the plug flow basin. The anaerobic and aerobic zones are not physically

separated. The boundary between zones is defined operationally at the point where DO and $\text{NO}_x\text{-N}$ concentrations rapidly increase above 0.2 mg/l.

At the DePere WWTP, the initial activated sludge tank operates anoxically because of $\text{NO}_x\text{-N}$ in the recycled sludge. As indicated by the high SBOD_5/SP ratio of 47, sufficient organic substrate is available for both denitrification and phosphorus release to occur simultaneously. The anoxic contact period typically averages 3.5 to 4 hours. Samples collected in this basin during the field investigation indicated $\text{NO}_x\text{-N}$ levels between 2 and 4 mg/l. Other data collected during the field investigation indicate that phosphorus release occurs in the anoxic basin with SP concentrations up to 10 mg/l.

It may be that anaerobic conditions occur within the biological flocs, permitting phosphorus release. If sufficient SBOD_5 is available, denitrification may occur outside the flocs, while residual SBOD_5 penetrates the interior of the flocs in a microenvironment devoid of $\text{NO}_x\text{-N}$. Thus, phosphorus release would occur under anaerobic conditions within the floc even though bulk fluid conditions are anoxic. This phenomenon would be analogous to the occurrence of denitrification under bulk aerobic conditions, as is common in oxidation ditches and other activated sludge processes.²² Therefore, if these assumptions are accurate, plants with low influent BOD_5/TP or SBOD_5/SP ratios would not achieve release of phosphorus because available substrate would be used for denitrification.

However, because of the generally acknowledged negative effects of $\text{NO}_x\text{-N}$ on phosphorus release, and the limited data base collected at DePere, additional study is required to determine the conditions necessary for phosphorus release to occur under anoxic conditions.

Aerobic Reactor Considerations

All of the plants investigated, with the exception of the DePere WWTP, operated in the plug flow mode of operation. DePere used a completely mixed aeration basin. The Little Patuxent WWTP changed from the step-feed mode to the plug flow mode to improve phosphorus uptake. Aeration basin HRT ranged between 2.6 and 14 hours. As noted earlier, operation of the Little Patuxent activated sludge system in the step feed mode was affected by low DO concentrations that limited phosphorus uptake, a short actual HRT of less than 2 hours, and feeding of influent near the effluent end of the basin.

At all the plants investigated, plant operators typically maintained DO levels above 2 mg/l. At the Little Patuxent and Reedy Creek plants, the DO concentration was increased to between 3 and 5 mg/l at the effluent ends of the basins for oxygenation of biomass before sedimentation to prevent the release of phosphorus in the sludge blankets. Sludge blankets of less than 1 foot were used in the secondary clarifiers, but analytical data indicated that some denitrification occurred in some sludge blankets. Release of phosphorus, however, was not observed, except at the Little Patuxent plant.

The DePere WWTP maintained DO levels above 4 mg/l as a safety factor against intermittent shock organic loads received at the plant from local industries. The DePere plant was the only plant that experienced typical diurnal load fluctuations. Flow equalization is employed at the PhoStrip plants to dampen out diurnal flow and load fluctuations, while at the Reedy Creek WWTP hydraulic loads remain fairly constant during theme-park operation, 14 to 16 hours per day.

Nitrification and Denitrification Effects

All of the plants investigated operated with simultaneous nitrification in the Bio-P removal process. During the field

investigation, all plants (except the Little Patuxent WWTP) completely nitrified (see Table 8). Recycle of $\text{NO}_x\text{-N}$ in return sludge to the anoxic or anaerobic zone (or stripper tank) of a Bio-P removal process inhibits process performance. An explanation for this may be that organic substrate is used for denitrification and is not available for phosphorus release. Additionally, in nitrifying mainstream processes, longer MCRTs are necessary to achieve nitrification, which reduces sludge production and, in turn, lowers phosphorus removal. However, the results of the field investigations showed that nitrification had negative effects on phosphorus removal but that the two processes were not necessarily incompatible. In addition, various levels of denitrification occurred in both Bio-P removal technologies evaluated. However, at the Little Patuxent WWTP, all TN removal was attributed to assimilation into the biomass wasted from the system.

Figure 7 presents a linear regression between effluent $\text{NO}_x\text{-N}$ and OP or SP concentrations. For this analysis, data collected during the field investigations were supplemented with data from historical operation at the Lansdale WWTP and results from the Pontiac, Michigan, A/O demonstration study. The correlation coefficient of 0.77 shows a clear correlation between these parameters. This regression analysis indicates that residual values of SP or OP below 0.5 mg/l require $\text{NO}_x\text{-N}$ values below 10 mg/l. Thus, nitrification reduced phosphorus removal at these facilities, but only at phosphorus values below 1 mg/l. We consider Figure 7 to be applicable only to mainstream plants with high BOD_5/TP (or SBOD_5/SP) ratios and to the PhoStrip process. It may be that for mainstream Bio-P processes with low ratios of BOD_5/TP , nitrification may significantly reduce phosphorus removal.

Secondary Clarification

TSS removals during secondary clarification effectively reduced suspended phosphorus concentrations in the secondary effluents

observed during the field investigation. Clarifiers were of conventional design with relatively small 3 to 4 m (10 to 12 feet) diameter center wells. Table 11 gives a summary of clarifier performance and related data.

Generally, these data indicate the processes studied operated in the typical range for secondary clarification of 16 to 32 m³/m³-d (400 to 800 gpd/sf). However, under these conditions, actual effluent TSS concentrations were close to advanced wastewater treatment levels of less than 10 mg/l. The Little Patuxent WWTP (35 m³/m²-d [860 gpd/sf]) in July 1984 was the exception, with a value of 26 mg/l TSS. TSS removal performance improved in April 1985, with an effluent concentration of 11 mg/l. Generally, the average sludge volume index (SVI) was below 100 milliliters per gram (ml/g), although the average at the Reedy Creek WWTP was 152 ml/g.

The Lansdale WWTP secondary effluent averaged 8 mg/l TSS for the 14-month historical period under PhoStrip operation, versus 11 mg/l TSS for a 7-month period where the PhoStrip process was not operational. Mixed liquor settling tests with a Kemmerer sampler indicated excellent settleability. After 30 minutes of settling, supernatant TSS concentrations were 2 mg/l. Plant personnel noted that settleability fluctuates with changes in PhoStrip operation, indicating that the anoxic SDT produces organisms that settle rapidly. Secondary effluent TSS concentrations were normally less than 10 mg/l during PhoStrip operation. Microbiological analysis of mixed liquor showed levels of filamentous organisms that were indicative of well settling sludge.

The Reedy Creek WWTP applied 1 mg/l of chlorine to the return sludge stream to control filamentous organism growth that yielded an average SVI of 152 ml/g for the study period. The reactor mode and operation may be the cause of the poorer settling characteristics of the mixed liquor solids. Filamentous organism growth and bulking has

Table 11 Summary of Secondary Clarifier Performance

Plant	Parameter			
	Side water depth, m (ft)	Effluent TSS, mg/l	Secondary clarifier overflow rate, $\text{m}^3/\text{m}^2\text{-d}$ (gpd/sf)	SVI ml/g
Lansdale	4.6 (15)	4	15 (380)	70
Little Patuxent				
July 1984	4.9 (16)	26	35 (860)	52
April 1985		11	31 (760)	112
Reedy Creek	3.9 (10)	13	15 (360)	152
DePere ^a	4.3 (14)	7	20 (480)	71

^aData for the first of two clarifiers in series.

been noted in anaerobic/aerobic systems having an anaerobic HRT greater than 30 percent of the total HRT, and in aerobic plug flow reactors with low DO concentrations.²³

An important aspect of any Bio-P removal process is the evaluation of the need for effluent filtration to remove suspended phosphorus. As noted previously, suspended phosphorus is primarily a function of the biomass phosphorus content. Clarifier performance at the plants evaluated during the field investigations indicated TSS levels below 10 mg/l were achievable with conventional clarifiers designed for secondary treatment. These findings suggest that conventionally designed secondary clarifiers can achieve these low TSS concentrations. Optimization of clarifier performance by designing for deep tanks, large flocculator center wells, and minimum sludge blankets can effectively insure these low TSS levels without filtration.²⁴

Solids Handling

All of the plants investigated effectively processed solids and minimized the recycle of phosphorus back to the mainstream process. Biological sludges were thickened aerobically, or combined with the waste chemical sludge from the PhoStrip process and gravity thickened. Two plants utilized DAF units for thickening. Two facilities used aerobic digestion to stabilize sludges. Anaerobic digestion was not employed. Additionally, the PhoStrip plants used the waste chemical sludge streams to partition phosphorus from the liquid stream and prevent recycling to the head of the plant. Sludge processing return water at the Little Patuxent WWTP was recycled to the PhoStrip reactor clarifier for chemical phosphorus precipitation.

The recycle of phosphorus from the solids handling processes was minimal. Mass balances performed for the Bio-P removal processes showed the percentages of influent TP recycled to the plant were:

<u>Plant</u>	<u>Percentage of influent TP recycled to plant</u>
Lansdale	1
Little Patuxent (July 1984)	9
Reedy Creek	<1
DePere	3

The data for the Little Patuxent WWTP includes recycle of the tertiary filter backwash. Solids processing of thickened waste activated sludge and scum at the DePere WWTP occurs periodically (approximately every 5 weeks) on a batch basis. During this operation, chemical conditioning wastewater, filtration returns, and flue gas scrubbing water all recycle phosphorus to the plant, which causes effluent TP concentrations up to 1.4 mg/l. Phosphorus released from the sludge during storage in the holding tank is chemically conditioned with ferric chloride and lime prior to dewatering and incineration. This prevents the recycling of most of the phosphorus back to the head of the plant. Effluent TP concentration returns to normal levels within 4 days after sludge processing.

DISCUSSION

The results of the field investigations and recent experience reported at other Bio-P removal facilities indicate that these technologies are capable of achieving effluent TP levels of less than 1 mg/l. The PhoStrip process has demonstrated capability to achieve this level of treatment at low influent BOD₅/TP ratios. Influent BOD₅/TP ratios for the PhoStrip plants studied as part of this evaluation were 8 and 14.

Mainstream processes are more limited by the influent wastewater characteristics. Process influent BOD₅/TP and SBOD₅/SP ratios are the chief empirical parameters that show the applicability of mainstream Bio-P removal processes for treating specific wastewaters.

Figure 5 indicates that a value of influent $BOD_5/TP > 20$ to 25 or $SBOD_5/SP > 12$ to 15 is required to achieve an effluent concentration of less than 1 mg/l OP or SP for mainstream processes. However, below these BOD_5/TP and $SBOD_5/SP$ levels, effluent OP and SP concentrations vary greatly because of factors not characterized by the BOD_5/TP or $SBOD_5/SP$ ratio.

For BOD_5/TP ratios less than 20 to 25, it appears that application of the mainstream processes should include separate nitrification facilities to reduce effects from NO_x-N recycle. Attendant with these ratios, the lower MCRT will provide additional sludge production for enhanced phosphorus removal. Based on the results of the technology evaluation, it appears that for influent BOD_5/TP values greater than 25, nitrification need not affect the ability to produce an effluent with less than 1 mg/l TP. However, it appears the design of the anaerobic/anoxic zone must provide for denitrification. A HRT greater than the nominal 1 to 2 hours may be required. Excessive recycle of NO_x-N to this zone could inhibit phosphorus release.

In evaluating the performance achieved at the Bio-P removal plants during the field investigations, it is important to note that actual flows at each plant were below design values and effluent TSS values were below permitted levels. Effluent TP quality projected to the permitted TSS levels based on actual SP or OP concentrations achieved and the percent phosphorus associated with effluent TSS are presented below:

<u>Plant</u>	<u>SP or OP, mg/l</u>	<u>Permitted TSS, mg/l</u>	<u>TSS percent phosphorus</u>	<u>Projected TP, mg/l</u>
Lansdale	0.7	20	2.3	1.2
Little Patuxent	0.1	10	3.9	0.5
Reedy Creek	0.4	20	3.8	1.2
DePere	0.1	10	2.4	0.4

The projected TP values indicate that suspended phosphorus would compose 40 to 80 percent of the effluent TP concentration. Thus, TSS removal is critical to achieve an effluent TP concentration of less than 1 mg/l, regardless of the type of technology applied.

CONCLUSIONS

Key findings of the Bio-P removal technology evaluation are:

1. Field investigations at four full-scale facilities showed that the PhoStrip and operationally modified activated sludge processes can achieve effluent TP concentrations of less than 1 mg/l under nitrifying conditions without tertiary treatment.
2. Effective removal of both soluble and suspended forms of phosphorus were required to achieve an effluent TP concentration below 1 mg/l. BOD₅ and TSS removals to advanced treatment levels accompanied these low residual phosphorus levels.
3. The PhoStrip process appears capable of meeting this level of treatment at lower BOD₅/TP ratios than mainstream processes owing to the operational flexibility of sidestream chemical phosphorus removal.
4. Good Bio-P removal performance in the operationally modified activated sludge processes was attributed to favorable influent wastewater characteristics, with BOD₅/TP ratios greater than 20 and SBOD/SP ratios greater than 12 to 15. Lower values of these ratios could reduce phosphorus removal in these processes.

5. Nitrification and denitrification were compatible with phosphorus removal at the plants investigated. Nitrification affected Bio-P removal performance, but only in situations where effluent TP concentrations were below 1 mg/l TP. Total nitrogen removal to levels below 6 mg/l required tertiary treatment.
6. Anaerobic conditions were not required to enhance phosphorus removal. Extended periods under anoxic conditions (for example, a 20-hour SDT in the PhoStrip process and a 3.8-hour contact period in the operationally modified process) provided an effluent TP concentration of less than 1 mg/l. Other factors such as availability of soluble substrate and concentration of oxidized nitrogen would affect this performance. Operation under anaerobic conditions would improve phosphorus release.
7. Sufficient phosphorus uptake in aeration basins was ensured by DO levels above 2 mg/l. Sludge blanket levels were maintained at less than 1 foot in secondary clarifiers to minimize the anoxic or anaerobic conditions that permit phosphorus release.
8. Effective solids processing at each facility reduced phosphorus recirculation to the mainstream process.

ACKNOWLEDGMENTS

Kenneth Schnaars and Sheldon Stone of Robert E. Lee & Associates, Inc., Green Bay, Wisconsin, assisted with field investigations at the Bio-P removal plants. C. Reed, and T. McKim of the Reedy Creek WWTP, D. Benner of the DePere WWTP, D. Ward of the Little Patuxent WWTP, and D. Shinski of the Lansdale WWTP and their staffs assisted in

testing and analysis during the special study periods and provided valuable insight into the Bio-P removal processes at their respective plants.

This material has been funded wholly or in part by the U.S. Environmental Protection Agency under contract 68-03-1818 to Brown and Caldwell Consulting Engineers. It has been subject to the Agency's review, and it has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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